ECOLOGICAL CHARACTERISTICS AND THE SUSCEPTIBILITY OF NON TARGET INVERTEBRATES TO LONG TERM PESTICIDE SIDE EFFECTS

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ABSTRACT

Criteria for evaluating the hazard posed by pesticides and the risk of non-target invertebrates suffering long-term side-effects are developed using basic information concerning life history. The trend for ecological factors to become more important than operational or toxicological ones in determining recovery rate following exposure is examined. The risk of organisms suffering long-term side-effects is related to their pattern of resource exploitation, dispersal rate and reproductive rate and correlated with life history strategies at different positions on the r-K spectrum. The consequences of this for the scale and duration of experimental studies is discussed.

INTRODUCTION

In order to obtain a quantitative expression of hazard, or the degree to which a pesticide will harm the non-target-invertebrate community, the level of risk (or the probability of being harmed) to individual species must be measured. This paper uses ecological criteria to define these two factors, assuming long-term effects to be those that persist into the following crop or season at statistically significant levels. (Short term, or within crop or season effects are not dealt with directly).

The use of ecological characteristics to describe organisms at risk is proposed as an alternative to the use of simple taxonomic criteria or economic importance. Taxonomic criteria are inappropriate given the diversity of the non-target-invertebrate community and the wide variation in abundance of individual species in space and time. It is impossible therefore to select particular groups that could be taken to represent the whole community. The selection or ranking of species by beneficial capacity or economic value is also unrealistic given the wide taxonomic and ecological diversity within the beneficial community (Jepson, in press). In addition the idea that the potential economic impact of pesticides (via resurgence and secondary pest outbreaks) can be predicted from their toxic effects on a small number of beneficial species arises from the mistaken assumption that predators and prey are in a simple coupled system. In the real world, a predatory complex of many species exerts a variable effect on any particular pest species.

This paper takes a novel approach by separating the non-target invertebrate community into groups with similar ecological characteristics. These groupings have arisen from the assumption that exposure to pesticides and the potential for recovery following this are likely to be affected by factors such as the proportion of life history

TABLE 1
Factors affecting the level and duration of pesticide impact on non-target invertebrates

BIOLOGICAL FACTORS	OPERATIONAL FACTORS
EXPOSURE TO PESTICIDES	
<u>At the time of spraying</u>	<u>At the time of spraying</u>
- proportion of population in sprayed area	- application volume
- degree of protection by crop canopy or soil refuges	- nozzle parameters and droplet spectrum
- droplet capture efficiency	- application frequency
<u>Following spraying</u>	<u>Following spraying</u>
- residual exposure: distribution pattern and diel activity cycle	- persistence and break-down of a.i.
	- formulation
- dietary exposure: availability of contaminated prey	- environmental influences on bio-availability
SUSCEPTIBILITY	
- genetic, structural and physiological factors, mediating uptake metabolism and toxic effect	- intrinsic toxicity of a.i.
	- application rate
- environmental factors mediating toxic effect	
RECOVERY/REINVASION	
<u>Direct ecological factors</u>	
- mobility/dispersal/timing	- persistence and breakdown in environment
- reproductive rate/voltinism	
- isolation/proximity to non crop reservoirs	
<u>Indirect ecological factors</u>	
- degree of oligophagy/polyphagy	- spectrum of activity and toxic effects on alternative prey items in substrate
- extent of depletion of preferred prey	
<u>Sub-lethal effects</u>	
- repellency	
- behavioural activation	

that a species spends within the crop environment and the degree to which immigration from non-crop areas contributes to field populations each season. The approach taken below is to review the biological and operational factors that mediate pesticide effects on non-target species and then to examine differences in ecological characteristics that may explain the range of effects detected in the field. The groupings which arise may then be used to aid interpretation of experimental results or to select groups for investigation during field studies (Sotherton et al., 1988).

BIOLOGICAL AND OPERATIONAL FACTORS MEDIATING THE LEVEL OF SIDE-EFFECTS

Table 1 summarises the factors that are likely to affect the level of pesticide effects on different species and the rate of recolonisation of the treated area. The importance of exposure and the temporal and spatial factors influencing it, are deliberately emphasised. Failure to give this factor sufficient priority has had an important effect on the design and interpretation of laboratory and field tests (Jepson, 1987). At the time of spraying, the canopy can provide substantial protection from direct spray exposure for epigeal organisms, especially in its later stages of development (Jepson et al., 1987). Initial exposure is also affected by the method of spray application, timing and frequency; the manipulation of these factors may provide a route to the more selective use of pesticides (Jepson, in press). Exposure following spray application is a function of pesticide bioavailability (Graham-Bryce, 1987) and invertebrate behaviour, distribution and diet. These factors have yet to be investigated in the arable crop situation.

Susceptibility of different species to the pesticide is of primary importance, given a certain level of exposure at the time of application. Its importance following application is likely to decline however, in relation to ecological factors such as dispersal rate which govern the rate and extent of reinvasion. This latter process will also be affected by the extent of pesticide effects on resource availability to certain non-target invertebrates.

This summary deliberately attempts to realign the focus of terrestrial non-target invertebrate testing methods towards the process of recolonisation and recovery following exposure to pesticides. This has implications for both the scale and duration of field tests and also on the relative importance of semi-field testing methods which may quantify the direct toxic effects of pesticides on selected species (Sotherton et al., 1988).

INVERTEBRATE GUILDS AND THE RISK OF LONG TERM EFFECTS

The invertebrate community exploiting resources available within arable crops such as winter cereals can be subdivided into guilds which group species with similar ecological characteristics. For example, the predatory arthropod community (feeding upon or parasitising aphid pests) may be divided into guilds of aphid specialists such as coccinellids, syrphids and parasitic hymenoptera which are highly dispersive, colonising infested crops following pest invasion, predatory groups such as staphylinids, which disperse into the crop from non-crop areas but which have a broader diet range and groups such as carabids that complete

all or part of their life-cycle within the crop and tend to be polyphagous feeders. Table 2 examines hypothetically, the extent to which the different biological and operational factors mediating side-effects (Table 1) will affect each of these guilds following spray application. It reveals that there will be a degree of separation between them in the relative importance of different factors and the rate at which they will recolonise the crop. In ecological terms, this separation is a result of differences in the pattern of resource utilisation (ie. exploitation of temporarily available prey on the crop or of a range of alternative prey items that inhabit the crop environment on a longer term basis), the level and extent of dispersal and reproductive rate.

In the real world, only a sub-set of organisms within each of these guilds will be exposed to pesticides and those organisms will exhibit a wide range of susceptibilities to the chemical concerned. Field experimental data will not therefore tend to reveal these trends on initial inspection. This only serves to emphasise the importance of defining guilds or other groupings at risk of long term effects, so that the effects on these species can be examined in detail. The table also reminds those planning experimental studies that toxicological and operational factors will tend to dominate the initial phase of effect but that differences in recolonisation and recovery rate will be most affected by ecological factors. The extent to which current experimental designs provide data on reinvasion and recovery by groups at risk is open to question.

A GENERAL MODEL OF RISK BASED ON LIFE HISTORY STRATEGIES

The ecological characteristics used above to classify the invertebrate guilds in winter cereals constitute important components of the life history strategies of the organisms concerned. These stratagies are the product of selection pressure within environments with varying degrees of temporal stability and patterns of resource availability. These pressures have tended to select organisms that exploit temporary resources and which have high dispersal capacities and reproductive rates and more sedentary organisms with low reproductive rates that exploit the resources within more stable habitats. These two extremes of population dynamics and life history are encompassed in the postulate of r and K selection (MacArthur and Wilson, 1967).

Table 3 is an attempt to represent the functional guilds of invertebrates inhabiting winter cereals according to their relative positions on the r-K spectrum of life history strategies. This exercise is intended to illustrate the probable importance of life history parameters in determining the rate and extent of recovery after pesticide exposure, it also forms a convenient way in which information on non-target invertebrate side-effects from other crops and environments may be interpreted. The table indicates those pesticide usage tactics which involve the highest risk of long-term side-effects (ie. delayed recovery) by organisms with different life histories. The additional component of frequency of use of pesticides has been included to represent the full range of options within the real world. The extent to which this matrix of possibilities supports or aids interpretation of specific side-effects field studies will be considered elsewhere however, it does indicate that

TABLE 2

Constraints on the recovery of the different functional guilds, within the beneficial arthropod community of winter cereals, present at the time of application of a broad spectrum pesticide

	TIME INTERVAL SINCE EXPOSURE TO PESTICIDE			
INVERTEBRATE GUILD	IMMED. FOLLOWING SPRAY APPLICATION	WITHIN SAME CROPPING PERIOD	THE FOLLOWING CROPPING PERIOD	MORE THAN ONE CROPPING PERIOD AHEAD
DISPERSIVE, PEST-SPECIFIC PARASITOIDS AND PREDATORS eg. Coccinellids Syrphids most Hymenopteran parasites		Potential for rapid reinvasion from outside crop, subject to availability of prey and toxicity of chemical residues	No persistent effects of previous application since pests inhabiting new crop form the resource to be exploited	Ditto
DISPERSIVE POLYPHAGOUS PREDATORS eg. Staphylinids some spiders and some parasitoids	Initial effect for all groups dependent upon exposure and uptake of pesticide and susceptibility of organism to specific pesticide. Ecological factors other than position at the time of spraying unimportant	If dispersal phase completed, little potential for recovery/ other groups as above	Some persistent effects possible via alternative food availability. Groups with soil active phase may be affected by residues	Persistent effects unlikely
FIELD RESIDENT POLYPHAGOUS PREDATORS eg. Carabids, some spiders		Little potential for recovery by wholly resident field species. Those entering from field boundary affected by residues and food availability	Recovery affected by rate of dispersal, and reproductive rate mediated by alternative food supply. Residues may also be important	Recovery may still be incomplete for slow dispersers or species sensitive to food availability. Scale of application important

strategic decisions in chemical pest control may have a significant effect on the extent of harm to different non-target invertebrate species.

This analysis looks beyond small-scale, within-season field experiments and examines the consequences of full scale commercial use of one or more pesticides. On this spatial scale and over long time intervals, the capacity of different species to recolonise treated areas is likely to be the most important component of pesticide side-effects. This is especially the case in an agricultural environment where the toxicity of individual products is declining but the general rate and frequency of use of insecticides is increasing.

THE CONSEQUENCES FOR FIELD TESTING METHODS

It is clearly unrealistic to examine a dynamic effect on the basis of one pesticide application, given the importance of spray timing in relation to the phenology of non-target invertebrates. It is also unsound to extrapolate effects detected within one season and on a small scale to side-effects that may arise on the scale of commercial use. Field experiments on these limited temporal and spatial scales must be seen as discriminating for some potential effects and not others ie. initial indices of toxicity to those organisms present in the crop at the time of spraying and not the duration of the recovery phase. If the most significant form of side-effects is seen to be delayed recovery by certain invertebrate groups, then a new methodology must be developed. This will inevitably not be able to simulate commercial use, especially in parts of the world where the scale and intensity of spraying are measured on a regional basis.

Tests on more than one site and with sufficient attention paid to plot size may however, be an effective first step. As a novel alternative, integrated laboratory and semi-field methods could examine the toxicity of pesticides to potential organisms at risk and the persistence of toxic residues on foliage and soil. They could also examine the spectrum of activity against the dietary items of non-target invertebrates such as microarthropods. Mathematical modelling and/or systems analysis would be required to examine the consequences of these effects on a realistic scale.

THE CONSEQUENCES FOR DEFINING SIGNIFICANT HAZARD

The most important feature of this ecological approach is that it views agricultural crops as a habitat, providing resources which are exploited by non-target invertebrates. Some resources are short-lived (eg. crop pests) and the invertebrates that exploit them are dispersive, and tend to have a high reproductive rate; in other words their life history strategies approach the 'r' end of the r-K continuum. Other invertebrates, resident within the field exploit longer term resources and their life history strategies approach 'K', in the r-K continuum. Changes in resource availability may elicit emigration away from the field, especially in the case of dispersive species. Changes may also cause intergenerational effects such as reduced fecundity or more subtly, increased susceptibility to environmental perturbations once populations fall below critical population densities. These latter effects may be

TABLE 3 Theoretical framework linking the probability of suffering long-term pesticide side-effects with life history strategy, operational factors causing these effects are given assuming commercial scale application in more than one season

RELATIVE POSITION OF ORGANISM IN r-K SPECTRUM			
r	INTERMEDIATE	K	RISK OF SUSTAINING LONG-TERM EFFECT
DISPERSIVE, WITH LONG POTENTIAL PERIOD OF CROP COLONISATION RAPID REPRODUCTIVE RATE, PROBABLY A DIET SPECIALIST	ENTERING CROP FROM NON-CROP AREAS WITH ONE OR MORE PHASES OF DISPERSAL. LESS RAPID REPRODUCTION, PROBABLY LESS SPECIALISED DIET	COMPLETING ALL OR PART OF LIFE CYCLE WITHIN CROP. UNIVOLTINE OR BIVOLTINE, POLYPHAGOUS	
Coincident with time of a broad spectrum persistent spray application used frequently and on a large scale	Species with one phase of dispersal sensitive within season. Also intermediate between r and K.	Use of toxic product at sensitive phase of life cycle or frequent use of low toxicity product. Treatments which affect diet. Combined effects of more than one product	HIGH RISK
Similar to above, but compound of limited persistence or scale and intensity of use reduced	Intermediate	Exposure to products applied before emergence or colonisation, especially non-persistent compounds. Limited effects on diet	INTERMEDIATE RISK
Compounds used outside period of colonisation or use of selective products	Intermediate	Selective pesticide compounds or application strategies. Reduced usage via IPM	LOW RISK

expected with invertebrates that have low reproductive rates and limited capacities for dispersal.

In this context, an ecological definition of significant effects will tend to look beyond initial impact to the following season to examine whether or not the quality of the field environment as a habitat for non-target invertebrates has changed. Thus changes in the resource base may be seen as being equally important in terms of consequences for long-term population dynamics as other effects on a field scale, and differences in life histories of the organisms concerned as being the dominant factors on a larger scale.

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DISCUSSION

R. Clements: I am fortunate to be working in grassland as many of the difficulties of doing this type of work really don't apply. For example, Dr Jepson quite rightly said that, in cereals, it is unrealistic to examine a dynamic effect of one pesticide application. I can see that, in cereals where a number of applications will be made in the year, it really must be very difficult to interpret observed effects. In grassland, of course, the situation is much simpler. We only have one application made every 5 or 10 years. Also, in our work only 3 small fields within a large farm were sprayed. This is a realistic representation of what normally happens. It is a very different situation to that in cereals and some other arable crops. We are fortunate in being able to work in a real life situation without worrying about scaling up effects from a one or two hectare plot to what might happen a 300 hectare field.

P. Jepson: This is a confusing area. Firstly, when I say it is unsound to look at a dynamic effect on the basis of one treatment, I am not concerned about commercial realism. I am talking about the way in which a highly fluctuating dynamic situation can respond to single applications. It would be a rare event to get a significant effect. You need to apply several times in order to investigate the range of effects you can get. The point is the nature of the numerical data we obtain and the biological variation, not the number of applications in cereals. Secondly, we are also trying to equate the long-term effects which are detected to the scale of commercial use of products. One problem that Dr Sotherton and I have highlighted is that even Boxworth is on a small scale to us. The commercial scale of use of a product, not just in cereals but in any crop, can be up to hundreds of thousands of hectares per annum in a small region. We are trying to consider those larger scale effects. It may be true that a sub-unit of grassland treatment is 2-3 hectares but, if chlorpyrifos treatment becomes widespread, you may, in an extreme case, have a patchwork of treatment over a whole region of the UK in any one year. That, to me, is a very different type of phenomenon which cannot actually be tackled by the research methodology that we have to-day. This is why Dr Sotherton and I suggest that modelling approaches and semi-field experiments should be used so that the mechanism and timing can be elucidated for the type of effects we find.

S. Rushton, Newcastle University: The mosaic system of chlorpyrifos usage in grassland in the UK presents a perfect system for multivariate analysis.

R. Brown: Dr Sotherton, you said that, however big the scale of your experiments, you always had the problem of being surrounded by unsprayed areas which caused re-invasion. Is the presence of unsprayed areas telling you something about the habitat? What should we be doing to identify the patchwork of spraying?

N. Sotherton, Game Conservancy: I don't think we need to look at the patchwork of spraying, but we do need to calibrate the rate at which animals are re-invading. That is a big gap in our current work. Only when that gap has been filled can we realistically interpret our findings.

T. Lewis: Would Dr Sotherton like to say how you can investigate that? Who is going to work on rate of re-invasion and on what scale? How many people? Are you talking about winged or wingless creatures?

N. Sotherton: I think we need to look at a range of species with a range of dispersabilities from, for example, collembola to hoverflies. In terms

of who is going to work on it, I think the answer is anybody who can generate the money to do it. I think it is an urgent priority and that all our current work is flawed by the lack of that information.

P. Jepson: Dr Lewis is highlighting the complexity of investigating such a phenomenon. However, there are ways of tackling it. Simon Duffield, for example, is treating plots of different sizes, from a fraction of a hectare up to tens of hectares, and looking at the rate at which organisms recolonise those habitats and then attempting to extrapolate that to a much larger scale.

R. Brown: I was intrigued by Dr Sotherton's suggestion that introduction of Good Laboratory Practice to much of our research might help. In industry GLP makes our job quite difficult in some cases. Would he like to expand on that?

N. Sotherton: I wouldn't, except to say that if standards are slack it is one way experimental practices could be tightened up.